GORDON FRASER

ANTIMATTER

THE ULTIMATE MIRROR

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Contents

I Science fiction becomes science fact

Scientists read newspapers and watch TV like anyone else, but do not expect to learn very much about their professional interests this way. They have their own ways of keeping abreast of new developments. The advance of science is carefully documented and has its own rules and protocol. But, in January 1996, it did not happen this way. Physicists all over the world, preparing to return to their research laboratories after an end-year break, were startled to learn from mass media reports that a small experiment had made a major breakthrough. 'Scientists create the fuel of science fiction', said headlines in *The Times* of London, 'Discovery could lead to a different understanding of the Universe' claimed the *Washington Post*; 'At the door of Antimatter' – *La Liberation*, 'The Gate of the Shadow Kingdom' – *Der Spiegel*. Digesting this media hype, physicists realized the experiment had synthesized the first atoms of antihydrogen, the simplest form of chemical antimatter.

This avalanche of scientific publicity was precipitated by a four-paragraph press release from CERN, the European Laboratory for Particle Physics in Geneva, Switzerland. The response was incredible – within hours this modest story made prime-time TV and hit the front page of major newspapers all over the world. News magazines in several languages had a field day. Strangely enough, it was exactly one hundred years after Wilhelm Röntgen in Würzburg mailed a letter reporting the discovery of strange 'X-rays' that had produced photographs of the bones in his wife's hand. The impact of Röntgen's discovery had been immediate, and popular newspapers teased the public with stories of 'all revealing radiation', and women were advised to wear lead-lined clothes to protect them from prying X-ray eyes. Broadcast via the internet, the CERN press release had an even more immediate impact than Röntgen's X-rays. But how had such a story caught the public imagination while the physicists were still in the dark?

The impenetrable quantum world defies understanding, but its very impenetrability can stimulate the imagination. What governs a realm of which we can form no coherent mental picture? Of all the bizarre scientific concepts of the quantum world, antimatter has become the stock of science fiction – a key to make the impossible possible. Fictional antimatter-fuelled spacecraft shuttle through the maze of space and time. Antimatter was science fact that was adopted by science fiction, but, in January 1996, that popular fiction reverted to science fact.

ATOMIC SEX CHANGE

In 1603, the German astronomer Johann Bayer plotted the positions of about 2,000 known stars in his Uranometria celestial atlas. Today we know that even our own galaxy, the Milky Way, contains about a hundred billion stars, more than ten times the human population of the world. Astronomers estimate that the Universe contains about a hundred billion galaxies, each of which must contain about as many stars as the Milky Way, so that the Universe must contain of the order of ten thousand billion billion (10^{22}) stars, as many grains of sand as would cover a country like the UK to a depth of several centimetres.

All the matter in our world, animal, vegetable or mineral, is made from atoms. But atoms are very small: there are more of them in a cube of sugar than there are stars in the Universe. Every one of these atoms in a cube of sugar is electrically perfect, but every one of these atoms is top-heavy. If there were such a thing as stellar genetics, it would be as though its laws had contrived to make every star in the Universe male.

The motive force of atoms is electricity. Atoms are composite things, but overall are electrically neutral, their constituents carrying equal amounts of positive and negative electric charge. Such a balance could result through individual positive charges inside the atom pairing together in electrical wedlock with negative partners. This is what has happened in some distant huge stars, where ordinary atoms have been crushed by the remorseless press of gravity. But, in the atoms we know, there is no pairwise matching – the segregation of the electrical sexes is complete, each atom having a cloud of negatively charged electrons orbiting a small positively charged nucleus.

Although the atom's electric charge is thus balanced, its mass is not. More than 99.9 per cent of the mass of our world is built of positive electricity. By taking atoms to pieces, we can make both positive and negative electricity, but in our world the former is heavy, while the latter is very light, and therefore much easier to make. Is this imbalance reflected in the entire Universe, or is there a compensatory world where the atomic mass is dominated by negative electricity? In a letter to the journal *Nature* in 1898, the physicist Arthur Schuster surmised 'If there is negative electricity, why not negative gold, as yellow as our own?' For thirty years, Schuster's conjecture gathered dust.

Physicists call the equations of certain theories 'beautiful', meaning they are concise, symmetric and self-contained, free of arbitrariness. If such equations say something can happen, it usually does. One example is the famous set of equations written down by the Scottish physicist James Clerk Maxwell in 1864. In the early nineteenth century, physicists had found that a current-carrying conductor generates a magnetic field, and a moving magnet generates an electric current. Electricity and magnetism are somehow reciprocal, dual forms of each other. The exact duality became enshrined in the counterpoint of Maxwell's equations for electric and magnetic fields.

In 1927, an equation written down by another British physicist, Paul Dirac, predicted a new duality which underlined what Schuster had suggested in 1898 (but by which time almost everybody had forgotten). By Dirac's time, physicists had discovered that atoms were like miniature solar systems, with electrons orbiting around the atomic periphery, and a central atomic nucleus containing protons. Unlike the solar system, electrons carried negative electric charge and protons positive, so that the distribution of electric charge inside the atom appeared as an outer negative cloud with a small positive centre. As well as carrying opposite charge, protons are much heavier than electrons, two thousand times heavier in fact, so that the electrons' contribution to the atomic mass is very small.

Dirac's new equation was supposed to describe the electron, and did so very well. But, in addition, it said that an electron must have a counterpart particle with equal but opposite electric charge. At first Dirac thought his equation belonged to the world he was used to. The oppositely charged particle in his electron equation was the proton, suggested Dirac initially. But the symmetry of Dirac's equation is the symmetry of the Universe itself, too perfect for its result to be so outrageously flawed, with one particle two thousand times heavier than the other. Beyond our top-heavy atomic world, Dirac realized, a complementary electrical symmetry has to exist, with a new kind of genetic material for its atoms. These new particles he called 'antiparticles'. This antiparticle world would be a mirror-image of our own, with its lightweight particles being electrically positive instead of negative.

After Dirac's time, physicists went on to discover many more kinds of subatomic particle, most of which are very exotic and not found inside ordinary atoms. Although not very relevant to our everyday world, these exotic particles were once part of the tapestry of the Universe in the first fraction of a second of its existence, when the temperature was about ten billion degrees. As the Universe cooled, these unstable particles decayed away and produced the structure we now know. Synthesizing these exotic particles requires supplying enough energy to recreate these primal temperatures. According to Dirac's theory, these particles too should have antiparticles.

In a piece of electrically neutral matter made up of ordinary atomic fabric, the electrical nature of the atomic structure is latent. However if the sample is put in a strong electric field, it becomes electrically distorted, with negative charges pulled to one side, and positive pushed to the other. The whole sample becomes electrically biased. When the surrounding electric field is switched off and the tension in the electrical elastic of the atoms is relaxed, the atomic charges twang back to their equilibrium position and the sample reverts to being apparently neutral.

There is an even more fundamental electrical resilience than the structure of atoms. At the creation, 'the earth was without form, and void'. The void is the flimsiest possible fabric, but even the electrical neutrality of this primordial void was split asunder into separate particles and antiparticles by the forces unleashed in the Big Bang, the explosion that gave birth to our Universe. The primordial elastic stretched in the Big Bang is still expanding, and the particles at one end of it have evolved into the world we know. But, wherever they look, physicists see only matter composed of particles. Where are the antiparticle counterparts on the other end of the primordial elastic? Particles and antiparticles appear to have gone their separate ways. But, wherever the mirror world of antiparticles is, one day it could return. When the forces of the Big Bang are finally spent, the primordial elastic connecting particles and their antiparticles could snap back and reconstitute the Void of Genesis.

Although physicists do not know where to find antiparticles, they have learned how to make them. Soon after Dirac's realization that antiparticles had to exist, in 1932 the first such antiparticle was found – the antimatter counterpart of the electron, very light and carrying one unit of positive electric charge, and therefore called the positron. The positron is a carrier of positive electricity. As physicists became more skilful, they discovered more and more examples of antiparticles. However, these isolated antiparticles are not primordial, they are not dredged from the seabed of creation. They are synthetic, created in processes which mimic on a small scale how the Big Bang first split the electrically neutral void into particle–antiparticle pairs.

Physicists gradually learned how to tame antiparticles, first positrons, then antiprotons, and built sources which supplied them on tap. But these antiparticles last only as long as the sources are kept supplied with power. As if jealous of their monopoly, matter particles greedily attack any intruder antiparticles, annihilating them to give bursts of radiation. Antiparticles have to be carefully protected, and during their protected lifetime usually remain lone antiparticles, without any allegiance to atomic shape or form. However, antimatter should obey the laws of chemistry as well as physics. Could synthetic antiparticles be used to make material – true atoms of antimatter? Even in copious supply, antiparticles invariably annihilated with the surrounding matter before carefully chosen particles and antiparticles could be 'introduced' to each other and provide the right conditions for atomic marriage.

THE FIRST ANTIMATTER

On 12 September 1995, almost a hundred years after Schuster wrote his speculative letter to *Nature,* a German physicist called Walter Oelert looked at his computer output and realized his experiment could have manufactured about a dozen atoms of antimatter. In 1993 and 1994, he had tried to achieve his goal where others had failed. Perhaps 1995 was third time lucky.

It had been a hectic few weeks, first with the experiment trying to beat the clock and then analysing the mass of resulting information. For just 48 hours over three weeks, the experimenters had been privileged to tap the most precious piped utility in the world – antiprotons. Many physicists bid for the prized antiprotons and Oelert's team were allocated just two days. By trading beam time with other experiments, Oelert was able to make the most of this narrow slot.

With the actual experiment complete, and with all the data securely piled up in the computer, then the second phase could begin – painstakingly sifting through the mass of accumulated information. A billion antiprotons had given 300,000 signals in the experiment's computer. From these, 23,000 counts had been selected as being right for further grooming, and were being carefully analysed one by one.

After two weeks of careful work, programming the computer to take account of everything the experimental team could think of, a few counts obstinately refused to fall by the wayside. 'I felt good', said Oelert. 'I was sure they were right.' The team turned to the rest of the data, and over the ensuing weeks, a total of eleven 'gold-plated' counts turned up. Were they what physicists had been waiting for most of the twentieth century to see, or were they just some cruel trick of statistics, wisps of data accidentally blown together to form a scientific mirage?

Oelert's experiment at the world's largest scientific laboratory, CERN, was a modest project by the standards of today's Big Science. The team numbered just sixteen physicists. Elsewhere at CERN, teams of hundreds of researchers were working on experiments worth hundreds of millions of dollars. Oelert's team used salvaged equipment. 'Compared to the big experiments, ours cost almost nothing', he claims.

The big physics experiments take years to plan, design and build. Then come more years of running and analysing data. The entire working life of a university researcher can be spent in a single such experiment. In contrast, Oelert's modest proposal had been submitted for approval in October 1994 and finally given the go-ahead in February 1995. Under the code-name PS210, six months later it was up and running. Approved and completed within one year, PS210 was not even listed in that year's edition of 'Experiments at CERN', the 500-page book which was supposed to list the 136 scientific experiments then under way at the laboratory. With attention focused on the big detectors and the politics of their highly international teams, few other people at CERN had even realized that PS210 had come into being. The researchers came and went almost unnoticed.

PS210's plan did not sound very spectacular. The plan was to fire a beam of antiprotons at a fine jet of xenon gas. Antiprotons do not exist naturally on Earth. They can only be synthesized, and there are two places where they are available on tap. CERN is one, the other is Fermilab, the US particle physics laboratory on the Illinois plain near Chicago. These particles are so precious that, even when an experiment is ready to run, the antiproton supply frequently has to be shared among several customers and even then is severely rationed. A small antiproton experiment like PS210 has to remain in a state of continual alertness, like runners in their starting blocks, waiting for the gun to fire. 'Once one of the students pressed the reset rather than the start button on one of the detectors, and we missed that antiproton spill', remarked Oelert wryly. But PS210, with its jet of xenon gas, had a new idea. The scheme was to use the beam of antiprotons to make still more antiparticles. With this double layer of antiparticles, there would be more chance of providing the right conditions for getting particles and antiparticles together and synthesizing atoms of antimatter.

To a beam of subatomic particles, the atomic structure of even a solid metal target looks like a mesh of chicken wire. Most of the time the particles in the beam pass straight through. Only a tiny fraction of it 'wets' the atomic mesh. Monitoring any experiment are the 'detectors', sophisticated surveillance systems taking a precision electronic snapshot each time a particle touches the target mesh. Each of these 'events', as the physicists call them, allows physicists to reconstruct what happened when the incoming particle actually hit something. As with any surveillance system, most of the recorded data is routine. The particle physicists, the policemen of the subatomic world, carefully watch for signs of anything unusual.

The experiment's computer scans the recorded data, carefully filtering off worthless background dross in the search for valuable nuggets. As in gold prospecting, the filtering frequently leaves the pan empty and the researcher/prospectors have to return to the source for more raw material. If, after repeated attempts, the experiment still reveals nothing, the experimenters move on to other territory. After a few such unsuccessful attempts, it is tempting to abandon the experimental territory and move on. But the history of physics is littered with examples of searches which have retrodden old ground and probed deeper, finally coming up with treasure. A researcher has to have imagination, insight and lots and lots of patience.

After the computer has scoured the data, occasionally the experimenters' efforts are rewarded by the flash of a bright nugget. Even then, all that glitters is not gold. Before staking an ambitious claim, the nugget has to be carefully assayed to ensure that it is not the proverbial flash in the pan. Again, science history is full of examples of premature announcements, bold claims which have not withstood the final acid test.

In science, staking a claim means writing a paper and submitting it

FIGURE 1.1 Walter Oelert (photo CERN). Walter Oelert led the team which discovered the first atoms of chemical antimatter.

for publication in a learned journal. This ‘scientific literature’ is not meant to be entertainment. Intended for other researchers, these papers are largely incomprehensible to those not working in the field. Even the most spectacular scientific advances are described in stilted phrases, using obscure terminology and incomprehensible symbols. Avoiding colourful language, the paper in time-honoured fashion sets out what the experiment is, how it was done and, finally, what it purports to have found. The paper that Oelert’s team was preparing spoke of ‘testing CPT invariance’.

PS210 had set out to make antihydrogen. Hydrogen has the simplest of all atoms – each ordinary hydrogen atom consists of a lone electron orbiting a single nuclear proton. Antihydrogen atoms would have a positron orbiting a nuclear antiproton. With eleven firm antihydrogen candidates, the PS210 team thought their dream had been realized. In November 1995, the final draft of their paper was polished and sent to the editorial office of *Physics Letters*, a leading European physics research journal. Eagerly Oelert and his team awaited the outcome.

The editor of a learned journal like *Physics Letters* is chosen for his knowledge and skill in appraising research claims. However, no single person can know enough about a complicated field like particle physics to judge every paper himself. The editor normally seeks the advice of a 'referee', a knowledgeable researcher not directly involved in the experiment who can act as an impartial judge. As well as filtering off over-optimistic or charlatan papers, this refereeing process can also work in the experiment's favour, leading to suggestions to improve the presentation and quality of the result. In principle, the authors of the paper do not know who the referee is, and all correspondence goes via the editor.

For Oelert's paper, the referee was Rolf Landua, a young German researcher also working at CERN. Landua, an imaginative but careful worker who in his youth was a German champion butterfly swimmer, knew well the difficulties involved. Replying to the editor, Landua said he was not convinced that all the eleven counts were antihydrogen. Perhaps, he suggested, some of them were due to antineutrons, another form of antiparticle. Because they were electrically neutral, these antineutrons could be mistaken for neutral antihydrogen atoms. Antineutrons had been seen forty years previously. PS210's handful of nuggets should be given further scrutiny, he recommended. Realizing the anonymous referee had a good point, PS210 set to work again.

While Landua was going over the draft paper, CERN had been preparing for the December 1995 meeting of its governing body, the Council. CERN is funded by twenty European states, and biannually, in June and December, national delegates come to Geneva decide on key issues. In December, the Council traditionally has to fix the budget for the coming year. Big science is big money, CERN's annual budget being some one thousand million Swiss francs, and in cost-conscious times this budget is frequently fiercely debated and haggled to a fraction of a percentage point.

CERN's business is pure research, the furtherance of knowledge and understanding. Although in the long run this knowledge ultimately leads to technological progress, in the short term the usefulness of pure scientific progress is not easy to measure. As the *New Scientist* once said when CERN's budget was under scrutiny, the worth of such a laboratory cannot be measured in terms of non-stick frying pans or even Nobel prizes. When quizzed about the usefulness of his apparently arcane researches into electromagnetism, the nineteenth-century British physicist Michael Faraday replied 'I cannot myself imagine what use it has, but I am sure that it will one day be taxable.' Faraday's researches ultimately led to the industries of telecommunications and of electrical engineering.

Despite these difficulties in evaluating the potential of new science, in his traditional December report to the Council on the year's research achievements, CERN's Director General is naturally keen to point to concrete results and show the assembled delegates, many of whom are diplomats or civil servants rather than scientists, that they are getting value for their research investment. Christopher Llewellyn Smith, the Oxford Professor of Theoretical Physics who became CERN's Director General in January 1994, had been planning to mention the PS210 antimatter discovery in his 1995 end-year review. Even when a significant discovery is made, the complexities of modern science make new developments difficult to explain to a lay audience. But the antimatter news was something most delegates would be able to appreciate at face value, and Llewellyn Smith had earmarked it as being speechworthy. However Landua's objections meant that any announcement of the result was premature, and Llewellyn Smith reluctantly had to stay silent on that count.

While CERN Council met, the fate of the PS210 result hung in the balance. Eleven counts surviving from 23,000 is not many, and, if most of them could be attributed to antineutrons, the experiment could not claim to have found anything. In the PS210 apparatus, the counters are segmented into three portions, each recording separately. All the data were still available for the computer, and by looking back at the way the eleven counts had been recorded in these triply segmented sensors, the experiment could tell if the signals were due to antineutrons. Carefully extending the analysis, only two of the eleven signals looked to have the characteristic antineutron signature. The PS210 team were overjoyed to find that nine bright nuggets remained. Immediately they told *Physics Letters*.

On 20 December, when most scientists were locking their laboratories and returning home for a two-week end-year break, the claims of PS210 were finally upheld and the paper was accepted for publication. The painstaking analysis had taken several months, and during this time rumours that the experiment had seen antimatter had begun to spread via the electronic grapevine of the internet. Curious scientists find it difficult to keep their mouths shut or their fingers away from their e-mail keyboards. Anxious to stop the spread of uninformed rumour, on 4 January CERN took the unusual step of issuing a press release on a scientific result before the scientific paper had been published.

CERN scientists preparing to return to work after the break were startled to hear the BBC World Service saying that antimatter had been discovered at their laboratory. CNN beamed a 64-second story worldwide. After exchanging 1996 New Year greetings and wishes, the CERN scientists eagerly sought further information. During the next few days, prime-time TV and newspaper reports piled up. The influential German weekly news magazine *Der Spiegel* ran the news as the cover story in its 15 January issue.

Walter Oelert was besieged by journalists. Arriving at Geneva for a day of newspaper interviews, he received a fax asking him to stay over until the following day so that a TV crew could also fly in. However the following day had already been reserved for another press interview, Oelert explained, this time in his home town of Jülich. After boarding the jet that evening to return to Germany, Oelert was watching the cabin crew make the final preparations for departure. Suddenly the cabin door reopened and a fax was thrust at the stewardess.

'Is there a Professor Oelert aboard?' she asked.

Oelert identified himself.

'You are asked to leave the aircraft immediately', she explained.

Oelert realized what had happened. 'I stay on this plane', he insisted.

The plane departed with Oelert on board, but it was clear that antimatter had arrived.